Version , To appear in Astronomical J.

Flickering faint galaxies: few and far between

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ABSTRACT

Optical variability in galaxies at high redshift is a tracer of evolution in AGN activity, and should provide a useful constraint on models of galaxy evolution, AGN structure, and cosmology. We studied optical variability in multiple deep CCD and photographic surveys of blank fields for galaxies with $B_j = 20 - 25$ mag. Weakly variable objects are far more common than strongly variable ones. For objects near $B_j = 22$, $0.74\% \pm 0.2\%$ vary by 0.026 mag RMS or more, over a decade. This is small compared with previous claims based on photographic surveys, and also small compared with the fraction of bright quasars ($\approx 5\%$ at $B_j = 20$ mag) or Seyferts ($\approx 1 - 2\%$ for $B_j < 18$). The fraction of objects that vary increases slowly with magnitude. Detection probabilities and error rates were checked by simulations and statistical analysis of fluctuations of sample sky spots.

Subject headings: galaxies: active — galaxies: nuclei —- surveys — galaxies: statistics — galaxies: photometry — techniques: image processing

1. Introduction

The existence of Quasars (QSOs) near redshift 5 (Schneider *et al.* 1989a, Schneider *et al.* 1989b, Schneider *et al.* 1994) and the recent discovery of a rapidly rotating 0.1 pc disk

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in a galaxy (Miyoshi *et al.* 1995) suggests that there are many black holes that predate galaxies and have accretion disks that vary noticeably over days to months (Turner 1991, Loeb & Rasio 1994, Eisenstein & Loeb 1995). Eisenstein and Loeb argue that more than 0.1% of early objects with baryonic mass in the range 10^6–10^7 $M_\odot$ have very low angular momentum and would settle within 10^6 yr to a ~ 0.1 pc compact disk, quickly evolving into a seed black hole. Given these seed black holes, one expects the seeded galaxies to have AGNs (Active Galactic Nuclei) and to exhibit optical variability when the black holes are accreting.

Models of the origin and evolution of activity in galaxies are constrained by the number density and variation amplitude of such galaxies. While variation of the optical luminosity of AGNs is known to exist on timescales of days to years, the AGN phenomenon has traditionally been studied via other indicators of activity such as line, radio, and X-ray emission (Balick & Heckman 1982, Rees 1984). Little is known of optical variability in unbiased samples of local galaxies, much less at high redshift where evolution of this phenomenon might be detected. Searches for early AGN activity via optical variability are a good way to investigate early compact objects, as variability over a 1 - 10 year period requires a compact (*i.e.*, less than 10 pc) source, such as a massive central black hole in a galaxy. The source must also not have much local obscuration, as light which has been scattered through large angles (thus randomly delayed) will have had its short-term variability smoothed away.

Large CCDs and gigabyte disks enable an accurate search for these effects. In this paper we present the results of high precision photometric monitoring of 2830 galaxies in a single $16'^2$ field (2345+007) over 13 epochs spanning 1984 to 1994. The mean magnitudes of the galaxies are $B_j = 24.8$ mag and $R = 23.3$ mag. We also compare our CCD data to photographic data from a wider $1.16^{\circ 2}$ field, whose objects have a mean magnitude of $B_j = 23.7$ mag.

2. Observations

The 2345+007 data used in this study were taken during on the CTIO 4-m, KPNO 4-m, and CFHT 3.6-m telescopes, over the period 1984 – 1994. A typical epoch consists of deep shift-and-stare exposure sequences (Tyson 1990) in B_j and R filter bands, reaching $B_j \approx 26$ magnitude ($26.5 B_j$ and $25.5 R$ mag arcsec^{-2} surface brightness 3σ threshold). The size of this survey field has increased with time from $2.5' \times 4'$ to $16' \times 16'$. Table 1 is a journal of these observations. Figure 1 [Plate 000] shows a composite color image of the central area of the field. In this image, the frames have been combined with a weighted

clipped average (Fischer & Kochanski 1994).

These images, and other "blank" field data taken during each run were used to generate a night sky superflat. The superflat was used to process the data, then all frames in a given color for a given epoch were aligned and combined by a soft-clipped average. The final images for each epoch are essentially free of radiation events and CCD defects. Calibration was obtained from transfer standards within this field (Tyson & Seitzer 1988) referenced to fundamental standards for the B_j & R system (Gullixson *et al.* 1995). For the purposes of this study we require only relative photometry; the brightness of each object is compared to the average of all other objects in the field. Relative photometric accuracies range from 0.01 mag to 0.05 mag for bright objects (see section 4, and figures 4 and 5).

As a check on our CCD survey, we also include data from a wider area photographic survey in Sextans with only two epochs. The photographic data consists of 48000 galaxies of 19 – 23 B_j mag in a $1.16° \times 1.16°$, two epoch survey from the 2.5m Dupont telescope at Las Campanas Observatory (Tyson 1995, Postman *et al.* 1995). Six of nine plates were used from a run on March 14-23, 1985, and three of four from a run on march 13-15, 1986. Exposure times were two hours on hypersensitized IIIa-J plates; the seeing was $1.2''$ FWHM on the combined images. The plates were scanned with $0.54''$ pixels, then density-to-intensity conversion was done on a per-pixel basis using CCD calibrations in five sub-fields within this large field. Thirty-four stars were used in the (nonlinear) calibration, with a RMS residual of 0.12 mag. Finally, the images were median-combined to reduce plate defects. Number counts of galaxies in this field are complete to $B_j = 25$.

3. Data Processing

The goal of this program is to determine the fraction of photometrically varying galaxies in the field as a function of magnitude and of the degree of variability. Relative epoch-to-epoch photometry is complicated by variations in seeing, CCD pixel size, exposure times, alignments and image scale between different epochs. In order to overcome these difficulties, we have developed software which performs pairwise comparisons between the overlap regions of different epochs. For each pair of observations, the individual epochs are geometrically transformed, convolved and scaled using a least-squares fitting algorithm, followed by the subtraction of one from the other. Photometry is done on the subtracted images, so that the diffuse parts of the galaxies (which are constant) cancel, and only the variable, unresolved nuclei appear.

For 2345+007, eighty-eight of the difference images were used, the software selects

$\approx Nlog_2(N)$ of the $N(N-1)/2$ images, somewhat arbitrarily, to keep the processing time reasonably small. The 2345-007 and Sextans datasets are treated independently until the last step, where a statistical description of galaxy variability is derived from a maximum likelihood estimator.

Objects in 2345+007 were defined by two *FOCAS* (Jarvis & Tyson 1981) detections on the same epoch (*e.g.*, B_j and R), or three detections in different epochs. For the photographic dataset, a detection in both epochs was required. Requiring that the object be present in both images eliminates hundreds of nominally variable "objects" from consideration that are apparent on only one image. Oversized areas were excluded for diffraction spikes and saturated regions of bright objects, edges, and obvious plate or CCD defects. In the Sextans field, this resulted in elimination of all objects brighter than ≈ 19 mag.

3.1. Image Subtraction

The image subtraction program, called *NLSFIT*, was written in C++, and built around a standard nonlinear least-squares fitting routine. The strategy is to fit one image to the other, in a model-independent manner, without the necessity of extracting and fitting luminosity profiles and positions, or pre-classifying objects as stellar vs. nonstellar. It provides precise matches between images without using isolated reference stars, such as deep images or crowded fields.

One advantage of our approach (subtraction followed by photometry) is that it is very insensitive to crowding effects. Since few objects are variable, neigboring objects will subtract out and not disturb the photometry on the difference image.

Before subtracting the images, we must adjust the point-spread functions of the images. Simply convolving one image with a smoothing kernel before subtraction to match point-spread functions (PSFs) is not appropriate; least-squares fitting algorithms assume that the errors in different data are uncorrelated. That assumption is violated by convolving just one dataset with a kernel. Because of this, a naive implementation will always over-smooth. Consider a single object in the midst of a large area of sky. The errors in the immediate vicinity of the object will be minimum when the smoothing is correct, *i.e.*, the PSFs are matched. However, the noise in the large area of sky will monotonically decrease as the smoothing is increased. The minimum of the overall error will be with the object oversmoothed, because the extra systematic mismatch introduced in the objects by oversmoothing will be compensated by a reduction of the random noise in the blank sky

between the objects.

The cure for these problems is to fulfill the formal requirements of the least-squares fitting algorithms. One must convolve the subtracted data by a kernel chosen to de-correlate or "whiten" the noise, so that errors on different pixels are independent of each other. This whitening kernel is typically a weak sharpening kernel, and when combined with blurring the sharper of the two images, results in an output image with a size intermediate between the sizes of the two input images (see figure 3). Appendix A describes the algorithm in more detail.

Figure 2 [Plate 000] shows the B_j band subtraction of the 1987 and 1990 epochs in the 2345+007 field, over approximately the same area as shown in figure 1 [Plate 000]. The mildly oscillatory nature of the kernels (insets in the figure) is apparent around some of the brighter stars. Figure 3 [Plate 000] shows the sum image corresponding to figure 2. The inserts are grey-scale representations of the two convolution kernels that are used to prepare the sum and difference images.

4. Photometry

After subtraction, we carried out photometry on the difference images, with an aperture weighted by a Gaussian with the same size as the PSF (for AGN searches) and three times that size (for SN searches). The larger aperture for the SN search allows detection of supernovae outside the host galaxy's nuclear region, and also provides a consistency check of the small-aperture AGN search.

The sky level for each measurement was derived from an annulus of pixels around the object of interest. The annulus extends in radius from 2 to 4 times the aperture FWHM; this was large enough so that sky noise is negligable compared to noise in the object. We excluded 50% of the annulus to protect against contamination from nearby objects. This was done by taking objects in and near the annulus, assuming a crudely modeled "average" galaxy of the appropriate magnitude sits on each site, and then taking the half of the pixels that have the smallest modeled contamination. Essentially, this punches out larger disks around brighter objects, without biassing the following mode operation against isolated bright pixels.

For sum images, a finite-width mode operation is used to derive a sky value. For difference images, since the histogram should be symmetric and objects have been largely cancelled out, the sky pixels are sent to a robust average operation. Pixels between the 15^{th} and 85^{th} percentiles are averaged; the tails are lightly chopped to reduce sensitivity to any

remaining image defects.

Corrections to the photometry are made for differences in the filter and CCD color response between the different epochs. This is done by requiring that luminosity differences between each pair of epochs must be uncorrelated with luminosity or color. These corrections can be significant, cancelling systematic photometric errors of typically $0.1(B_j - R)$ magnitudes. We also allow for excess noise from neighboring bright objects.

For bright objects in 2345+007, the RMS photometry errors range from 0.015 mag for B_j photometry with a larger (3×PSF) aperture to 0.032 mag for R photometry with the small aperture (aperture FWHM equal to PSF FWHM). These are averages over all images, and are ascribed to the input images; errors on difference images would typically be $2^{0.5}$ times larger. We assume that these errors are residual gain errors after flat-fielding the CCD, and that their magnitude decreases as $N^{-1/2}$ as more shift-and-stare images are combined (as suggested by a fit of residual errors to N). Thus, the large-aperture photometry on the best B_j image is assigned errors of 0.01 mag. Fainter objects are dominated by Poisson noise, which we measure from the variability of blank sky spots.

The small apertures do give a somewhat larger scatter for the brightest objects (*e.g.*, 0.026 *vs.* 0.015 mag in B_j), but are sized for minimum noise for faint objects, where photon statistics from the sky dominate the errors, rather than the PSF mismatches, pixelization, and gain errors that are important for bright objects. In the faint object limit, photometry with an aperture that matches the PSF shape and size is optimal (Fischer & Kochanski 1994). In addition, small apertures minimize contamination of photometry by crowding effects.

We checked these accuracies by comparing them to the RMS scatter of the calibration stars. Our calibration stars have a median magnitude of $B_j = 23.2$ and $R = 20.8$, and we get RMS residuals in calibration of 0.02 mag in R, 0.04 mag for the large B_j calibration, and 0.1 mag for the small aperture B_j calibration. These residuals are accurately predicted by our noise model.

In the AGN search, we assume that only the nucleus of the galaxy varies – any light outside the central area is diffuse light from large numbers of individual stars. So, it is appropriate to use a small aperture even on extended galaxies when searching for AGNs.

Since the Sextans data is from photographic plates, the noise is a complicated function of intensity and aperture size (*e.g.*, Dainty & Shaw 1976). We used a phenomenological noise model obtained from the data. The model was calculated independently for each 1530x1530 pixel region of the Sextans field. The noise models calculated for different areas agreed well (within 20%). The photometric data was first processed with a crude noise

model, so that χ^2 was calculated for all objects against a model of constant liminosity. The χ^2 values were binned, a median was taken in each bin, the photometric noise was calculated from the median, and the resulting values were fit with

$$Var(I) = exp(R(asinh(I/\sigma))), \tag{1}$$

where $R(x) = (a_0 + a_1x + a_2x^2 + a_3x^3)/(1 + bx)$ (a_i and b are fitted parameters), and σ is the sky noise. After this procedure iterated to convergence (two passes), the noise model accurately represents the photographic plate noise characteristics. Using the median prevents the model from being affected by a few variable objects. In practice, after we excluded objects with noticeable diffraction spikes, we found that we had excluded all saturated objects, and a somewhat simpler functional form would have sufficed.

Photometry errors for the small aperture AGN search (figure 4) and large aperture SN search (figure 5) are shown. The Sextans data is deeper, and more precise, despite the fact that it is photographic data. While some of the 2345+007 epochs have long exposure CCD images, many of the larger CCD images (table 1) are short exposures. The plotted curves for 2345+007, which are area-weighted averages of the photometric errors, tend to emphasize the large area exposures. Fainter than approximately 22 mag, the errors are dominated by photon statistics (for 2345+007), or photographic grain statistics (for Sextans). Sextans errors rise dramatically for objects brighter than 19 mag as the emulsion saturates, however these bright objects have already been removed because they contribute substantial diffraction spikes and epoch-dependent ghost images from stray reflections. Figures 4 and 5 are discussed further in the next section.

4.1. Detection of Variability

Given these photometric data, we must decide if a given galaxy is variable, and then if the variability is more likely due to an AGN or a SN. To do this, two statistics are computed for each location: a variability statistic, and a Supernova (SN) discriminator. The variability statistic is χ^2 of the brightness fluctuations, while the SN discriminator is the luminosity difference between the brightest epoch and the average of all others, divided by the noise of that difference. A supernova will typically appear as a single bright epoch, and thus will have a large discriminator. Conversely, an AGN, with its random fluctuations, will have a discriminator in the neighborhood of two.

We now need to set the smallest possible threshold for detection of RMS variability, while retaining good confidence that the object really *is* variable. To determine the statistical significance, we follow a set of blank sky points through the entire processing

procedure, in parallel to the set of real objects. We can thus measure real significance levels, rather than assuming that the noise is exactly Gaussian.

The variability and SN statistics for the sky spots are binned by the number of observations of each spot (N), and the tail of the cumulative distribution function (CDF) for the bins was fit to a empirical power-law function.

$$CDF(\chi^2) = 1 - ((\chi^2 - p_m)/(p_c - p_m))^{p_x} \tag{2a}$$

$$p_m = c_{a1}(N-1)^{c_{a2}} \tag{2b}$$

$$p_c = c_{c1}(N-1)^{c_{c2}} + p_m \tag{2c}$$

$$p_x = c_{x1} + c_{x2}/N \tag{2d}$$

where p_m, p_c, and p_x are empirical functions of the number of images that an object is within. More specifically, p_m is a fit to the median of the statistics as a function of N, p_c is a fit to the value of χ^2 where $CDF = 0.9$, and p_x is the exponent of the power law, and is fit over the range $0.9 <= CDF < 1.0$. The CDF is 1 minus the false alarm rate, *i.e.*, the probability that the observation would have been produced by chance. In fact, we find the tails of the distribution of χ^2 to decline more slowly than would be expected, typically as $\approx (1 + x^2)^{-2.5}$ for false alarm probabilities near 10^{-3}, rather than the expected $exp(-x^2/2)$.

As a check of equation 2a, we ran yet another set of locations through the entire processing procedure, from photometry to detection of variability. This check set was chosen from a uniform distribution across the area (to simulate the uniform density of faint galaxies), rather than selected blank locations. The different spatial distribution allows us to confirm that our corrections to the noise model for proximity to bright objects are indeed correct. This check set returns the expected number of false variables, within statistical uncertainties.

Figure 6 shows the distribution of χ^2 statistics for the Sextans objects. The difference between the statistics for the objects and blank sky spots is apparent. The 2345+007 histogram is similar, but has substantially fewer objects. Objects were declared variable when the false alarm rate went below 5×10^{-4} for the 2345+007 dataset, and 3×10^{-4} for the Sextans dataset. These false alarm rates correspond to one false claim of variability out of six variables in 2345+007 and 6 of 80 for Sextans. We used a lower threshold for the Sextans dataset simply because we had more data available and could afford to be more selective. The different thresholds were consistently applied during the measurement of the classification probabilities, so that the final statistics (after the maximum likelihood estimator) would be independent of the exact value of the threshold. Objects were then classified as SN, AGN, or uncertain, depending on the value of the SN discriminator.

Figures 4 and 5 displays photometry errors and variability-detection thresholds versus magnitude. Figure 4 displays errors on the small aperture AGN search, and figure 5 the large aperture (SN search). The thresholds for detection of variability are $3-6$ times higher than the $1-\sigma$ photometry errors, and are shown by the cloud of dots, one point per object. In general, each object has a unique detection threshold because of three factors. First, the noise is a function of brightness. Second, in the 2345+007 dataset, the noise will differ from region to region, depending on which images (which epochs) cover a certain region. Finally, the few points that are near other objects have increased noise because changes in the PSF from epoch to epoch change the blending of the images.

Almost all the objects that were seen to be variable show a fairly small variability, the vast majority having $\delta M < 0.3$ mag. In fact, most of the detections are not far above the respective threshold, an observation that implies that there is no well-defined, distinct set of variable objects. Instead, we are sampling the tail of a broad distribution of variability, which may encompass all galaxies.

4.2. Simulations

Finally, we measured the various variability-detection probabilities by adding simulated AGNs (Gaussian intensity fluctuations with a $f^{-1.5}$ power spectrum) and simulated SNe (data sampled from an average type-Ia light curve from Dogget & Branch 1985) to the actual photometric results for blank sky spots. We then counted how many of the varying objects were recovered. We were also able to quantify the probabilities of misclassification (*e.g.*, a SN classified as an AGN). Figure 7 shows the two classification and four misclassification probabilities for the 2345+007 dataset. As these curves are measured by adding variability to blank sky spots, they are the appropriate probabilities for faint objects where the noise is dominated by sky statistics. For brighter objects, we scale these curves by the ratio of the object's noise level (*e.g.*, including CCD gain variations) to the sky spot noise level.

By multiplying the variability-detection probability for AGNs by the number of galaxies per unit magnitude, we find that we have the most information about galaxies with 0.1 mag variability at $B_j = 23.5$ or $R = 22.0$ magnitude. This dataset thus provides an excellent test of Hawkins' claims of large variability fraction at 23 B_j mag (see discussion below). Galaxies with smaller variability must be correspondingly brighter in order to have a sufficiently large signal to noise ratio to be clearly variable; galaxies with 0.03 mag variability would show up predominantly near $B_j \approx 21$, depending somewhat on the color and aperture size. Our variability-detection limit, for a 33% chance of detection, when averaged over the 2048^2

pixel CCD field, is $B_j = 24.5$ mag, for an object with RMS(δL)/L= 1. At this magnitude, we still have a a near-unity probability of seeing such variation if the AGN or SN occurs in the central, deepest area, where all the fields overlap.

5. Statistical Analysis

The goal of the analysis procedure was to determine parameters and error bars that answer basic questions about the statistical distribution of variability in the galaxy population. The basic questions are: "How many galaxies vary by X mag?", "does the incidence of variability change with apparent magnitude?", "is the $z \approx 0.3$ supernova rate similar to the local rate?". To accomplish this, the objects and the detection and classification probabilities were then fed into a maximum likelihood estimation routine.

This routine takes as input the measured classification probabilities as a function of the variability, and a model describing how much a given galaxy varies as a function of its apparent luminosity. We calculate first the probability (in an ensemble of universes) that we would detect each particular galaxy to be variable. Next, we calculate the overall probability that (in the ensemble) we would have detected as variable those specific galaxies that we *actually* detected to be variable. This overall probability is the likelihood of the model – it answers the question "How likely is it that *this* model would have reproduced the results we actually obtained?"

The model is parameterized, and the program varies the parameters to obtain the model with the maximum likelihood. It then obtains error bars by inspecting how fast the likelihood drops off as different parameters are varied by a simulated annealing algorithm. Information comes both from the galaxies that are seen to be variable and those that were not; both help to constrain the model.

We used either a seven or eight parameter minimization. One for dependence of AGN activity on luminosity. Two parameters to define the distribution of AGN variability (overall amount of variability, and shape of the probability distribution). Two parameters to define SN activity (SN rate and mean magnitude relative to the galaxies). Sometimes (as a test) one parameter was added that gave the AGN variability on the Sextans field, independently from the 2345+007 field. Finally, there are two parameters to match the 2345+007 and Sextans datasets (see appendix B).

5.1. AGN

The classification probabilities (*e.g.*, the probability that an AGN will be detected as variable and classified as a AGN) contain all the information on the performance of the analysis software. We then specify a model probability distribution for AGN variability, and how that variability might depend on apparent luminosity. The model contains no detailed physics, but is simply a phenomenological description of the probability that a galaxy will change its apparent luminosity by δL. Then:

$$P(\delta L/L) = C(L/L_0)^{\eta} \max(\delta L/L, \delta_{cut}/L)^{\zeta}, \tag{3}$$

where δ is the RMS variability of the luminosity, L is the luminosity of the object without the nucleus, η describes the trend of variability with luminosity, ζ and C describe the relative scarcity of strongly variable galaxies, L_0 is an arbitrary luminosity scale, and δ_{cut} is a cutoff, chosen so that $\int_0^\infty P(r)dr = 1$.

This parameterizes the amount of variability of galactic nuclei as a power law probability distribution, chosen because there is no evidence that normal galaxies and AGNs are physically distinct populations. For instance, the mass function of Seyfert 1 nuclei has been measured to be a broad power law distribution that does not require any natural separation between Seyferts and normal galaxies (Padovani *et al.* 1990). There is no published evidence that X-ray or radio luminosities have a truly bimodal distribution, rather than merely classification by an arbitrary detection threshold. Even if AGNs and quiet galaxies were distinct populations, the common model of AGNs as dusty doughnuts surrounding a black hole accretion disk (Antonucci 1993, Coleman & Dopita 1992) would give a broad distribution of apparent properties for AGNs, depending on orientation.

It is important to note that we compare the variability of the AGN to the luminosity of the rest of the galaxy, rather than the total luminosity. The total luminosity can be contaminated by an arbitrarily large amount of nuclear light (for instance, in a typical quasar, the nuclear light dominates the diffuse starlight from the host galaxy). The luminosity of the host galaxy is important, because it can be directly related to the distance and the mass of the galaxy. Consider a total luminosity L_t in the photometric aperture which is the sum of a nuclear component and a normal galaxy component, L, due to diffuse starlight: $L_t = L_n + L$. We assume, somewhat arbitrarily, that the average value of L_n is equal to its RMS variation (for the 2345+007 dataset), for the purpose of calculating the luminosity of the underlying galaxy. L_n is assumed to vary with a $f^{-1.5}$ power spectrum (Gopal-Krishna *et al.* 1995, Mangalam & Wiita 1993) and thus the normalization is somewhat different for the Sextans dataset, with its two closely spaced epochs. The same power spectrum leads to a smaller variance for Sextans, as it spans approximately one year,

rather than ten.

We conducted six separate maximum likelihood estimations of the astrophysically interesting parameters. We used objects detected (as variable) with the small aperture search only, objects detected with the large aperture search only, and the full search. The full search classifies objects as supernovae or AGNs, depending on whether they have more significant variability in the small or large aperture (SNe are likely to be off-center, while AGNs are not). Maximum likelihood estimates of parameters were then made both with the Sextans AGN density equal to the 2345+007 density, and with the Sextans density floating free.

The raw parameters are strongly correlated. We found it simplest to express the results in terms of the fraction of galaxies at a certain magnitude that vary by more than a given cutoff. We then search for the characteristic magnitude and cutoff that result in the strongest statement (smallest error bars) when all six sets of estimates (with error bars) are lumped together.

For $B_j \approx 22$ objects, $0.74\% \pm 0.2\%$ are AGNs that vary by 0.026 mag or more, RMS, over the period of observation. We find that the probability of a galaxy having a variability δM (near 0.026 mag) varies as $(\delta M)^{-3.3\pm0.8}$ (*i.e.*, $\zeta = -3.3 \pm 0.8$).

We find that the threshold for observing a constant fraction of variable AGNs changes by just a factor of 1.2 ± 0.1 per magnitude, or equivalently, that the fraction scales as apparent luminosity to the $\eta = -0.68 \pm 0.3$ power. Given that the comoving QSO density is maximum at a redshift of 2, one might expect the optical variability in 22-25 mag AGNs would increase somewhat with magnitude. The faintest of these galaxies would still be at redshift ≈ 1, so that by going from 22nd to 25th magnitude we would be primarily moving out the tail of the AGN luminosity function.

5.2. Supernova Probabilities

In the maximum likelihood estimate, we take supernova rates to be equal for all galaxies. Ideally, we would make the rate proportional to the absolute luminosity, but without redshift information, we cannot discriminate distant luminous galaxies from dwarf galaxies, nor easily compare rates with local measurements. There are thus two parameters: the rate of type-Ia supernovae, and the mean difference between the SN peak magnitude and the host galaxy magnitude. We include SN-Ib and SN-II in our calculations, scaled by the ratios obtained from Van Den Bergh 1994. For most of the galaxies, though, only the brightest SNe (*i.e.*, type-Ia) can be detected.

We find that the number of SNe we have observed is small compared to the number of AGNs. The rate is consistent with local SN rates in the vicinity of 1 per century per galaxy (Tamann *et al.* 1994, Evans *et al.* 1989). However, with current software, we cannot accurately measure the supernova rate in these galaxies, as the answer is too sensitive to systematic errors in the detection probability measurements. The small probability of misclassifying an AGN as a SN (Figure 7, compare at $B_j \approx 23$) yields a number of misidentifications comparable to the number of detections of real supernovae. Our detection probabilities are relatively low for SNe because our sampling interval is typically one year; supernovae will often flare and fade between our observations. Thus small errors in the classification probabilities lead to large errors in the supernova rate. To some extent, this is an intrinsic problem. There is no reason why an AGN cannot simulate a supernova light curve, especially one that is sparsely sampled and at relatively low signal to noise.

5.3. Variability Cross Checks

We have four independent tests of our variability detections. First, for the 2345+007 data, we can search for variability separately in the B_j and R bands, and compare results. If the galaxies are really variable, it is likely that there is substantial correlation between the two bands, so we would expect the two sets of variables to be strongly overlapping. Figure 8 shows the 2345+007 variable objects. It can be seen that there is substantial commonality, suggesting that most of these detections are indeed real. For instance, if we consider objects where the probabilities of detection of variability are fairly large, such as those brighter than 23^{rd} mag in B_j, we see that 0.6% are detected in R, and 0.8% in B_j. If the detections were independent, we would expect only 0.005% common detections, whereas we see 0.3%. Clearly, objects detected as variable in one color are much more likely than average to be detected as variable in the other color. The simplest explanation for this is that these objects are truly variable.

As a second test we compare overall variability rates in Sextans and 2345+007. The data are taken with dramatically different techniques, and suffer from different defects and systematic errors. Nevertheless, we get a consistent fraction of variable objects. The fraction of variable objects differs by only a factor of 1.4 (with Sextans higher) easily within combined errors. This discrepancy can be attributed to a deviation of the AGN fluctuation spectrum from the assumed $f^{-1.5}$ exponent, because the length of the two datasets is so different. Agreement of two such disparate datasets is supporting evidence that our analysis is operating properly.

Third, we have run a end-to-end test on the 2345+007 dataset, introducing artificial

AGNs into the input images by multiplying corresponding areas of each epoch by a random number with unit mean, and a standard deviation of 0.1 mag. Since the multiplication is conducted after the sky level is subtracted, it has negligible effect on the sky, but it makes all objects in the chosen area variable by 0.1 mag. We then check that the number of objects that we classify as variable agrees with our classification probabilities derived from simulations beginning after photometry (figures 4 and 5).

In the end-to-end test, there were 14 objects in the area that are bright enough to have an expected variability-detection probability (at a 0.1 mag variability) larger than 1%. The expected number of detections is 3.8, calculated from the area-averaged detection probabilities; we detected 7 objects as variable. Since our test area was in the central region, where all the images overlap, the detection probabilities are certainly expected to be better than the areal average, which includes large areas covered by only three or four images. This test is thus consistent with expectations. The seven detected objects were among those with the top nine precalculated detection probabilities, thus supporting the validity of our detection probability calculation. Additionally, all seven detections were correctly classified as AGNs.

Finally, we have also scrambled the epochs in the Sextans data, combining frames from both epochs into two independent images that have no time ordering. This scrambling will convert a truly variable object, that shows large differences between the two epochs into one with nearly identical luminosities on both scrambled images. On the other hand, the character of the noise on the scrambled images will not change; specifically truly constant objects will show the same RMS difference between images as they do between epochs. These temporally mixed images were processed identically to the real Sextans dataset. They yield variability detection rates one fourth as large as the Sextans data combined into their proper epochs. All these detections are spurious, and they provide an estimate of the number of errors in the real dataset.

None of these tests are conclusive, yet overall, it seems likely that our result is a fairly accurate measurement of the true number of variable objects.

There are also a number of partial cross-checks performed on various parts of the process. For instance, the calculation of the statistical significance of detections is checked as described in section 4.1 with a set of random sky locations. The photometry routines used here were checked against DAOPHOT, by comparing magnitudes and error bars of the two (gravitationally lensed) images of QSO 2345+007, for each epoch; results were consistent. As mentioned in section 4, we compared errors derived from our calibration stars to the measured epoch-to-epoch scatter of bright objects, and the overall noise model.

Images of variable objects were inspected epoch by epoch to look for imaging problems. In the central region of the 2345+007 image, we checked the list of object postions that we monitor for variability against against *FOCAS* detections on the full combined image (Figure 1 [Plate 000]). We have also added simulated SNe to the input images in earlier versions of the software, and checked that the number of retrieved SNe is consistent with the variability-detection probabilities shown in figure 7.

6. Discussion

The variable (and possibly variable) objects in 2345+007 are shown in figures 10 [Plate 000] and 11 [Plate 000]. Objects that were classified as variable on any of the nine searches (small aperture, large aperture, or combined) x (R, B, or combined) are shown. The figures show the actual CCD conditions; bad pixels were marked by hand and excluded from the analysis procedure. Variable objects in Sextans are shown in figure 12 [Plate 000]. Here, we can see the advantage of separately digitizing every photographic plate and median combining plates. No plate defects are visible amongst the variable objects.

Table 2 summarizes the properties of individual objects in 2345+007 that are clearly variable. Most of the objects that we see are blue (figure 8), and unresolved (figure 9), and they could be interpreted as faint AGN, distant QSOs, or perhaps variable stars.

We can compare these results with those of Hawkins (Hawkins 1986, Hawkins 1993) fairly directly. For the smallest threshold Hawkins applies (0.3 mag), we extrapolate a 3σ upper limit of 0.012% of the objects varying that much. This is more than two orders or magnitude smaller than his result. Our variability fraction, even neglecting our lower threshold, is approximately one tenth of his. These results are also much smaller than those of Trevese *et al.* (Trevese *et al.* 1989, Trevese *et al.* 1994) who searched for faint variable objects with $B < 22.6$ with a $\sigma > 0.1$ mag threshold on photographic plates. They found 64 variables out of the 694 objects with stellar PSF, (seeing=$1.6''$) from a total of nearly 1000 objects. This implies a variable fraction of 9%, two orders of magnitude higher than our results, but their restriction to objects with a stellar PSF is expected to give them a sample somewhat enriched in AGNs. Again, the threshold above which they will notice variability is higher than ours, so they should see only a small fraction of the AGNs we find. Our extrapolated 3σ upper limit is 0.15% variable objects. Both of those papers have investigated a sample of their objects spectroscopically, and both found that they did a reasonably good job of finding QSOs.

We see only two reasonable conclusions. Either AGN variability changes dramatically

near $B_j = 21$, or prior searches have suffered from systematic errors that have led them to spuriously claim non-variable QSOs to be variable. There are few statistics on the distribution of optical variability in AGNs. Clearly, some vary significantly on 1-10 year time scales (Schramm *et al.* 1994a, Schramm *et al.* 1994b), but most seem to be relatively constant. For instance the Hamburg Quasar Monitoring Program finds that most QSOs vary smoothly, typically by less than a tenth of a magnitude per year (Borgeest & Schramm 1994). Many of these quasars could not easily have been seen to be variable by prior monitoring programs, as the use of photographic plates forced variability-detection thresholds of 0.3 mag or more. The only published claim that nearly all quasars vary dramatically is based on the same Hawkins dataset (Hawkins & Véron 1993).

We believe that our CCD data is more reliable than previous photographic searches. Our practice of median-combining images from the same epoch eliminates defects and reduces gain nonuniformities. We also believe that our subtraction technique may cancel much of the systematic errors from which photographic plates suffer. We note that the Sloan Digital Sky Survey will search for variables on a very large area, at a slightly brighter magnitude range. It should provide a useful check of our result.

7. Variable Stars

What fraction of our sample of variable objects could be stars? Stars, particularly population I stars, are known to be variable. In our galaxy's disk, only intrinsically faint stars would be candidates, because of our faint apparent magnitude range. We integrate the luminosity function from Kirkpatrick *et al.* over a disk with a 350 pc scale height (similar to that suggested by the recent MACHO (Cook *et al.* 1994) and OGLE (Paczynski *et al.* 1994) results), and expect 20 disk stars in our magnitude range in the 2345+007 field. The dominant contribution comes from M-dwarfs with $V \approx 12$, which have a space density of $\approx 10^{-2}$ mag^{-1} pc^{-3}; such stars are relatively likely to be variable, as flare stars. Our variable objects are divided roughly evenly between bluish objects with $B_j - R \approx 0.6$ and red objects with $B_j - R \approx 2.3$; the former group is rather unlikely to be a stellar population, but it is not unreasonable to assume that the red half of our our variables may be M-dwarfs.

Halo stars have much lower space density ($\approx 10^{-4}$ mag^{-1} pc^{-3}), but the halo is large, so that bright stars can contribute from several kiloparsecs away. The intrinsically brightest stars ($M_v \approx 9$) are the most common, as the sampled volume is so large; it is the termination of the main sequence at $\approx 0.7\mathrm{M}_{\odot}$ that limits the sampled volume, rather than the size of the halo. The total number of stars, using the Dahn *et al.* 1995 luminosity function in our field is ≈ 250. Unlike disk stars, very few halo stars are variable, due to

their age and low metallicity (Boeshaar 1995). While we cannot accurately estimate the number of variable stars in our field, the possibility that a subset of our variable objects may contain some stars makes our upper limits stronger, and even less in agreement with previous photographic surveys.

8. Predictions of microlensing

Microlensing from dark matter has been tested in a variety of mass ranges (Dalcanton *et al.* 1994, Loeb 1994, Press & Gunn 1973). Our data can provide microlensing constraints, but they are generally weaker than produced by the MACHO survey (Cook *et al.* 1994). Microlensing of AGNs or quasars is difficult to disentangle because the constraints contain equal amounts of information about quasar structures as they do about the lens. The mass range to which we are most sensitive is $10^{-4}M_{\odot}$-$10^{-1}M_{\odot}$, for AGNs which have a milliparsec hotspot. We can show that this mass range contributes less than $\Omega_r < 0.1$, assuming that 1% of objects have milliparsec cores, or alternatively, we can show that less than $0.1\%/\Omega_r$ of galaxies in our magnitude range have milliparsec hot spots.

The importance of microlensing to the AGN phenomenon has been suggested for some time (Vietri & Ostriker 1983, Vietri 1985, Ostriker & Vietri 1986, Schnieder 1986, Nottale 1986) though generally from a theoretical perspective. Recently, Hawkins (1993) has claimed such an interpretation for the variability of 18-22 mag galaxies he finds in photographic photometry of patrol plates taken over a decade. Baganoff & Malkan 1995 provides an opposing view; see also Lacey 1994 and Schramm *et al.* 1993 for statistical discussions of microlensing and quasar variability.

9. AGN structure

The nearly-standard model of an AGN is an accretion disk surrounding a black hole, with energetic particle beams along the rotation axis, and a dusty torus in the plane of the disk (reviewed by Antonucci 1993). The observed variability will be a strong function of the viewing angle. As yet, there is little information on what fraction of the AGNs are oriented to give us an end-on view of the accretion disk, and what fraction present us with the dust clouds (with light scattering through the dust). A crude approximation can be obtained by comparing the density of BL Lacetae objects, which are presumably AGNs viewed end-on (Perlman *et al.* 1995). to quasars or AGNs. In a magnitude limited sample, derived from the ESO catalog (Véron-Cetty & Véron 1993), we find that the BL-Lac to QSO or AGN

ratio is near 1% (See Brown & Marchã 1993 for a discussion of the uncertainties of BL Lacertae counts).

Our data can place some constraints on this model. We can expect to see variability from a "bare" accretion disk; the time scales for light travel time across the disk is short. However, an obscured accretion disk is another matter. Even with small obscuration (*e.g.*, 1 mag), the variability of the source can disappear if the obscuring region is more than a few parsecs across. With a large obscuring region, photons will scatter, and will take paths with perhaps years of extra time delay. This will smooth out the variability by averaging the light curve with many different time delays. Similarly, if we are not seeing any accretion disk light directly, but instead we are seeing photons generated from axial beams, we will not see any variability if the scattering out of the beam occurs over a region larger than a few tens of parsecs.

If we make the reasonable assumptions that all accretion disks are intrinsically variable (Mineshige & Shields 1990, Clarke & Shields 1989), and that obscured accretion disks don't vary on our time scale, then we will just see BL Lac-like objects as variable. We would thus expect substantial variability in 0.01%-0.05% of objects - a small fraction of the total AGNs. This number is comparable to what we observe, given the uncertanties in the estimates, and helps rationalize our observation that so few objects vary.

It should be possible to use the exponent, ζ, that describes the shape of the probability distribution of variability (equation 3), to get information about the structure of the scattering regions around the accretion disk in AGNs. If one is willing to make assumptions about the distribution of variability in accretion disks, it may be possible to calculate how long photons must be delayed in the scattering regions in order to produce the observed distribution of variabilities.

10. Conclusion and Summary

In the first large, deep, multi-year CCD search for variable objects, we have turned up far fewer candidates than found by previous photographic searches. We have confirmed this by median-combining a set of photographic plates to form nearly defect-free images of another area, and have obtained a consistent, small, number of candidates.

For $B_j \approx 22$ objects, $0.74\% \pm 0.2\%$ are AGNs that vary by 0.026 mag or more, RMS, over the period of observation. We find that the probability of a galaxy having a variability δM (near 0.026 mag) varies as $(\delta M)^{-3.3\pm0.8}$.

We acknowledge the help of the expert staff at CTIO, where most of the CCD data were acquired, and the assistance of Ata Saradjenini at KPNO. Pat Boeshaar, Carol Christian, and Pat Waddell helped with the CFHT runs. Gary Bernstein allowed us to use some data. We gratefully acknowledge Rick Wenk for help in the reduction and calibration of the Sextans data, Marc Postman for scanning those plates, Rogier Windhorst for the Sextans plate acquisition. Ethan Vishniac and Michael Redmond for helpful comments. Support for this work was provided by NASA through grant # HF-01069.01-94A from STScI which is operated by AURA, Inc. under NASA contract NAS5-26555.

A. Algorithms for Matching PSFs

The *NLFS* program that fits together and subtracts images operates as follows:

First, since the program is used in a highly automated routine, there are a number of sanity checks on the data and the initial parameters, so that the program will not produce silly results from silly data.

There is an outer loop that calls the fitting routine, progressively allowing more parameters to be variable with each pass. A luminosity scale and the sky levels are freed first, followed by the coordinate transformation, then a single parameter to specify the smoothing scale, and finally the other smoothing parameters.

The fitting routine is a Marquardt algorithm for weighted least squares fitting. Weights are set by the Poisson noise for each pixel.

However, before the fitting routine can be allowed to run, the data must be prepared. The routine will not tolerate a variable number of data, so bad pixels (marked by IEEE-754 Not-A-Numbers in the incoming data) are identified, and a mask is made that specifies that those and nearby pixels will be ignored. Similarly, pixels near the edge are masked off. The mask is generated generously, so that invalid data will not be used, even as the parameters (*e.g.*, the coordinate transformation) change during the fitting.

Finally, we identify blank sky, and mask off most of it, so that we really only pay attention to the parts of the image near objects. This is mostly a time- and memory- saving technique (we can thus ignore 90% of the image), but also makes NLSFIT safer. Safer, because the errors are not dominated by Poisson noise from the blank sky (which contains no useful information), thus we are less dependent on precise knowledge of correlations in the noise of neighboring pixels. Safer also, because the algorithm becomes less sensitive to approximations we make in calculating the correct convolution kernels.

Inside the fitting routine, we calculate differences between the two datasets, on a grid of output pixels (with some masked off holes). The output coordinate system is chosen to be intermediate between the two input systems. Care must be taken to have a smooth and well-defined phase relationship between the input and output coordinate systems, otherwise shifting Moiré fringes will spoil the smooth relationship between parameters and the error measure that the fitting routine depends on.

The differences between the two datasets are calculated by convolving each dataset by an appropriate kernel, then interpolating each to the output coordinate system, and subtracting.

The heart of the program, though, is the calculation of the convolution kernels. From some of the parameters, we construct a kernel, κ, that shows how much we will smooth one image, *relative to how much we smooth the other.* If the input images are I_1 and I_2, and the output images are O_1 and O_2, then $O_1 = I_1 \cdot q$ and $O_2 = I_2 \cdot q \cdot \kappa$, where q is also a kernel. We find q from the constraint that the noise in the final (sum or difference) image must be white in order to fulfill the assumptions of the fitting routine. If our output image is $O = O_1 \pm \alpha O_2$, then the noise in O is $\tilde{O} = \tilde{O}_1 + \alpha^2 \tilde{O}_2$, where $\tilde{O}$ is the noise autocorrelation function (or noise spectral power density) of O. This may be expanded to yield $\tilde{O} = \tilde{I}_1 \cdot q^2 + \alpha^2 \tilde{I}_2 q^2 \cdot \kappa^2$, and solved in Fourier space for q: $q^2 = \tilde{O} \cdot (\tilde{I}_1 + \alpha^2 \tilde{I}_2 \cdot \kappa^2)^{-1}$. We can then require that $\tilde{O}$ be white and normalized to have unit variance: $1 = \sum \tilde{O}$. This has the nice feature that the total sum-squared errors on a noise image (or one where the subtraction of two objects is perfect) is constant and unity; anything above that is due to a misfit between the two images.

In general, these kernels must be truncated, so that convolution operations can be done on real space. Convolution in Fourier space makes it impossible to handle isolated bad pixels (*e.g.*, saturated stars), and makes it difficult to handle images where the sky background is not precisely flat. Additionally, real space colvolutions are faster, if the kernel is sufficiently (smaller than about 7x7). Since the kernel size cannot be changed inside the least-squares fitting routine, one of the functions of the outermost loop is to estimate a suitable kernel size, based on the previous iteration.

The input noise autocorrelation functions ($\tilde{I}_1$ and $\tilde{I}_2$) are functions of the fitting parameters through the pixel scale of the images (more generally, the coordinate transformation matrix). Imagine fitting a HST image to a typical image from a ground-based telescope. The HST image has a pixel scale *e.g.*, four times finer than the other image. In *NLSFIT*, the output image would have an intermediate pixel scale (*e.g.*, twice as fine as the ground-based image), so each ground-based pixel would be used twice. When that image is interpolated to the scale of the output image, before convolution and

subtraction, adjacent pixels will then be highly correlated. On the HST image, we are seriously undersampling, and there would be no correlation between pixels at all.

The actual parameters in the software unfortunately do not bear any simple relationship to either the smoothing or sharpening kernels. To keep the fitting routines operating smoothly, we found it necessary to arrange a functional form where χ^2 is a smooth function of all the fitting parameters, with continuous first derivatives, including the point where the images have identical PSFs. To a first approximation, though, the smoothing kernel is the sum of an elliptical Gaussian of variable size, and an elliptical exponential PSF of the same size and orientation. The exact functional form is not critical, as the kernel here is only supplying difference between two PSFs (which are approximately the same size). The relevant parameters are the size, the relative amounts of Gaussian and exponential (*i.e.*, long tailed or non-Gaussian shape), and two terms to specify the elipticity and orientation.

B. Matching 2345+007 and Sextans datasets

We have only weak information for the Sextans field on whether a given variable object is an AGN or a SN. Since there are only two epochs, we cannot discriminate on the shape of the light curve. However photometry (and all the analysis) is done on both a tight aperture (the size of the PSF) and a larger one (3 times the size of the PSF). Objects are classified as to whether their variability is more significant with the large or small aperture.

As AGNs are generally in the center of galaxies, the small aperture should pick up all the signal and a minimal amount of sky noise. Thus, faint AGNs dominated by sky noise should be statistically more significant in the small than the large aperture. Supernovae will typically be slightly off-center in a galaxy, and thus will, sometimes be more significant in the large aperture than the small one, especially for $z < 0.2$. Rather than attempting detailed simulations that depend upon unknowns such as the spatial distribution of SNe and black holes in galaxies at high redshift, we finessed the problem by including the classification probabilities for the Sextans dataset as model parameters.

The maximum likelihood procedure gives these two matching parameters properly wide uncertainties, but properly propagates the small amount of information from the spatial distribution into the rest of the parameters. It also propagates information on AGN-to-SN ratios from the 2345+007 data back into the Sextans dataset. Pragmatically speaking, the above paragraph only has a noticeable effect on the final SN to AGN ratios, a parameter without sufficient signal-to-noise ratio to make any meaningful claims.

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This preprint was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— A color image of the central region of the Q2345+007 field, reconstructed from 26 hours of B_j and R CCD exposures. North is up and east is left; the image is $200''$across.

Fig. 2.— The changes in the Q2345+007 field in B_j between the 1987 and the 1990 epochs. The point-spread functions of the two epochs have been matched by *NLSFIT* before subtraction.

Fig. 3.— The sum of the B_j band images of the 1987 and the 1990 epochs, processed through *NLSFIT*. The imaged region is the same as above; the grey scale is $asinh(signal/noise)$ (*i.e.*, approximately logarithmic). Image addition was done by *NLSFIT*; it convolves the two images with kernels chosen to produce white sky noise (*i.e.*, pixels are uncorrelated) in the sum and difference images. The two convolution kernels are shown in the insets, with the left operating on the 1990 data and the right on the 1987 data before addition or subtraction. The final PSF of the sum image is roughly intermediate between the two input PSFs, but is not guaranteed to be Gaussian, and can contain some oscillatory structure, as is seen here.

Fig. 4.— Photometry errors for 2345+007 (solid line) and Sextans (dashed line) fields as a function of magnitude for the small aperture search (aperture size equals PSF size). Poisson noise (photon statistics) limit the noise for objects fainter than $\approx$ 22 mag, and saturation of the photographic plates is significant for objects brighter than 19 mag. The variability-detection thresholds for individual objects are shown as dots. The threshold changes from object to object depending on the number of overlapping frames in which a particular object was imaged, so the variability-detection thresholds of uniformly imaged areas areas tend to form smooth curves on this plot. Both Sextans and 2345+007 variability-detection thresholds are plotted for both small aperture and large aperture searches. Objects that were actually detected as variable are shown as hexagons, with their measured variability (true variability plus noise) plotted as the y-axis. Clearly, there are few objects with strong variation; many are marginal detections.

Fig. 5.— Photometry errors for 2345+007 (solid line) and Sextans (dashed line) fields as a function of magnitude for the large aperture search. Poisson noise (photon statistics) limit the noise for objects fainter that $\approx$ 21 mag, and saturation of the photographic plates is significant for objects brighter than 20 mag. The variability-detection threshold (individual dots) are several times higher, depending on the number of overlapping frames in which a particular object was imaged.

Fig. 6.— Histograms of the distribution of chi-squared statistics for the Sextans objects (upper) and blank sky spots (lower). The number of objects between the curves is the number of variable objects. Some objects (*e.g.*, near $-log_{10}(P_{false}) = 4$) can be used statistically, but we cannot be certain which of those objects are variable. The 2345+007 histogram is similar, but has fewer surveyed objects and correspondingly fewer variables.

Fig. 7.— The classification (including four misclassifications) probabilities for the 2345+007 dataset. The right axis is the probability of detecting a type-1a supernova; it is small because a supernova can flare and fade in the ≈1 year interval between images. The top curve for the left axis is the probability of detecting a SN and classifying it as an SN, as a function of the magnitude of the SN. The left axis is the probability of detecting an AGN to be variable, and the top curve is the probability of correctly classifying it as an AGN. AGN probabilities are plotted against the average magnitude of the stellar nuclear component, with an assumed variability of $\delta L/L = 1$. Arrows on the figure show which axis to use. These probabilities are shown for faint objects ($B_j < 21$) where the signal to noise ratio is limited by photon statistics from the sky background.

Fig. 8.— The 2345+007 variable objects plotted on a color-magnitude diagram. Variable objects are shown as a "+" (B_j) or "x" (R), to allow comparison. Circled points are variable in the other color with lower (99%) confidence. It can be seen that there is substantial commonality, suggesting that these objects are indeed variable. A substantial fraction of the very bluest objects are seen to be variable, and are likely QSOs.

Fig. 9.— The 2345+007 variable objects plotted on a size-magnitude diagram. Size is plotted as the square of the FWHM (full-width at half max) of a Gaussian fit to the object, with seeing subtracted. Variable objects are shown as a "+" (B_j), or "x" (R), to allow comparison. Circled points are variable in the other color with lower (99%) confidence. Many of the variable objects are unresolved. The sequence of unresolved objects is particularly apparent for bright objects (*i.e.*, brighter than 20^{th} mag, and size-squared$= 0 \pm 0.1''^2$.

Fig. 10.— B_j band images of variable and possibly variable objects in 2345+007. Each image is $18''$ across, centered on the object, and is a composite of as many epochs as are available at that position. The seeing and noise thus vary somewhat from image to image. Intensity is plotted as $asinh(Brightness/Noise)$, which produces a nice logarithmic scale for bright regions, yet behaves smoothly near zero (sky) brightness. The list of objects used is a composite of all detections in either the B_j or R searches.

Fig. 11.— R band images of variable and possibly variable objects in 2345+007. Intensity is plotted as $asinh(Brightness/Noise)$. Each image is 18″ across, centered on the object. Images are paired, B_j and R bands, with the preceding figure.

Fig. 12.— B_j band images of variable objects in Sextans. Intensity is plotted as $asinh(Brightness/Noise)$. Each image is 18″ across, centered on the object.

Table 1. Journal of Observations

Date (dd/mm/yy)	Observatory	CCD	Scale ″/ pix	Filter	Exp. (sec)	FWHM ″
24/10/84 - 25/10/84	CTIO	RCA 320 × 508	0.59	B_j	7 × 900s	1.6 - 1.9
23/10/84	CTIO	RCA 320 × 508	0.59	B_j	1 × 500s	1.5
23/10/84	CTIO	RCA 320 × 508	0.59	R	11 × 500s	1.2 - 1.3
09/11/85 - 10/11/85	CTIO	RCA 320 × 508	0.59	B	8 × 500s	1.3 - 1.6
17/09/87 - 19/09/87	CFHT	RCA 340 × 528	0.41	B_j	31 × 500s	0.8 - 1.1
17/09/87 - 19/09/87	CFHT	RCA 340 × 528	0.41	R	11 × 500s	0.9 - 1.1
24/10/89 - 25/10/89	CFHT	RCA 340 × 512	0.41	B_j	9 × 500s	0.8 - 1.0
24/10/89 - 25/10/89	CFHT	RCA 340 × 512	0.41	R	9 × 500s	0.7 - 1.0
18/08/90	KPNO	Tek 1024 × 1024	0.47	B_j	3 × 300s	1.2
17/08/90	KPNO	Tek 1024 × 1024	0.47	R	3 × 300s	1.0 - 1.1
23/09/90 - 24/09/90	CTIO	TI 800 × 800*	0.58	B_j	20 × 300s	1.2 - 1.5
23/09/90 - 24/09/90	CTIO	TI 800 × 800*	0.58	R	25 × 300s	1.1 - 1.3
08/09/91	KPNO	Tek 1024 × 1024	0.47	B_j	3 × 300s	1.2 - 1.3
08/09/91	KPNO	Tek 1024 × 1024	0.47	R	3 × 300s	1.0 - 1.1
08/12/91	KPNO	Tek 2048 × 2048	0.47	R	3 × 720s	1.3 - 1.4
26/10/92 - 27/10/92	CTIO	Tek 1024 × 1024	0.48	B_j	12 × 500s	1.3 - 1.7
26/10/92 - 27/10/92	CTIO	Tek 1024 × 1024	0.48	R	13 × 400s	1.2 - 1.6
23/06/93	CTIO	Tek 2048 × 2048	0.48	B_j	6 × 500s	1.2 - 1.5
11/01/94	CFHT	Loral 2048 × 2048	0.21	R	3 × 600	0.7
30/08/94	KPNO	Tek 2048 × 2048	0.47	B_j	6 × 500s	1.3 - 1.4
30/08/94	KPNO	Tek 2048 × 2048	0.47	R	6 × 500s	1.3 - 1.4
24/09/94	KPNO	Tek 2048 × 2048	0.47	B_j	6 × 500s	1.3 - 1.4
24/09/94	KPNO	Tek 2048 × 2048	0.47	R	6 × 500s	1.3 - 1.4

*Rebinned to 400 × 400

Table 2. Variable Objects in 2345+007

Object ID	RA [2000] (hms)	DEC (dms)	mag (B_j)	$B_j - R$ (mag)	size ($arcsec^2$)	No. images (B_j,R)	χ^2/N (B_j,R)
G1379	$23^h\ 47^m\ 41.0^s$	0 deg 59′ 3″	23.6	0.8	-0.4	2, 4	0.1, 16.5
G2735	$23^h\ 47^m\ 42.0^s$	1 deg 2′ 58″	22.2	1.6	0.1	2, 3	6.8, 17.3
G386	$23^h\ 47^m\ 38.7^s$	0 deg 54′ 40″	21.9	1.1	0.2	2, 3	0.0, 16.8
G442	$23^h\ 47^m\ 40.1^s$	0 deg 54′ 28″	22.6	1.8	0.2	2, 4	0.0, 17.2
G5158	$23^h\ 48^m\ 11.5^s$	0 deg 57′ 0″	22.0	0.4	-0.3	6, 7	45.4, 9.1
G5740	$23^h\ 48^m\ 12.7^s$	0 deg 57′ 49″	23.7	0.4	-0.1	9, 10	198.5, 33.1
G5740	$23^h\ 48^m\ 12.7^s$	0 deg 57′ 49″	23.7	0.4	-0.1	9, 10	198.5, 33.1
G5876	$23^h\ 48^m\ 6.5^s$	1 deg 0′ 42″	22.0	0.5	0.5	2, 6	13.7, 4.4
G6659	$23^h\ 48^m\ 16.5^s$	0 deg 58′ 16″	23.7	2.1	-0.3	10, 11	3.8, 11.4
G6697	$23^h\ 48^m\ 19.1^s$	0 deg 57′ 17″	20.6	-0.0	-0.3	10, 11	15.4, 12.8
G6789	$23^h\ 48^m\ 19.5^s$	0 deg 57′ 20″	19.3	-0.1	-0.4	10, 11	43.9, 23.1
G6789	$23^h\ 48^m\ 19.5^s$	0 deg 57′ 20″	19.3	-0.1	-0.4	10, 11	43.9, 23.1
G7676	$23^h\ 48^m\ 11.8^s$	1 deg 3′ 0″	23.3	0.1	-0.2	2, 3	1.0, 18.8

Note. — This table shows objects detected with the small aperture search, in either B_j or R bandpasses. The color is the central color, resulting from the small aperture search. The size is the FWHM of the central peak, with seeing quadratically subtracted out, as derived from moments in the photometric aperture (negative numbers reflect errors in FWHM measurements). The number of images column notes how many of the observing runs imaged each variable object in each color. G6697 and G6789 are the quasar A and B images, respectively.